ES.1. EXECUTIVE SUMMARY

ES.1.1 Introduction

The North American Technology and Industrial Base Organization (NATIBO) undertook this corrosion detection technologies study to assess the industrial base, maturity, level of use, utility, and viability of corrosion detection technologies for land, air and sea applications. From this analysis, conclusions regarding these technologies and their further commercialization are discussed. The recommendations addressing these conclusions are then provided for potential future action. Joining the NATIBO in this effort for the first time is the Australian Department of Defence.

ES.1.2 Technology Overview

ES.1.2.1 Corrosion Fundamentals

Corrosion of metal in military systems is a highly complex phenomenon and takes many different forms. The result of all corrosion is the loss of strength of the material and the structure. Understanding the various forms and combinations of corrosion is essential to determining the importance of each and to finding the most appropriate technologies for detection and characterization of corrosion.

The following table summarizes the types of corrosion that can damage structures and their characteristics.

Table ES-1. Corrosion Types and Characteristics.

Corrosion Type	Cause	Appearance	By-Product
Uniform Attack	Exposure to corrosive environment	Irregular roughening of the exposed surface	Scale, metallic salts
Pitting	Impurity or chemical discontinuity in the paint or protective coating	Localized pits or holes with cylindrical shape and hemispherical bottom	Rapid dissolution of the base metal
Inter-granular or Exfoliation	Presence of strong potential differences in grain or phase boundaries	Appears at the grain or phase boundaries as uniform damage	Produces scale type indications at smaller magnitude than stress corrosion
Crevice	Afflicts mechanical joints, such as coupled pipes or threaded connections. Triggered by local difference in environment composition (Oxygen concentration)	Localized damage in the form of scale and pitting	Same as scale and pitting

Corrosion Type	Cause	Appearance	By-Product
Filiform	High humidity around fasteners, skin joints or breaks in coating cause an electrolytic process	Fine, meandering, thread-like trenches that spread from the source	Similar to scale. Lifting of the coating.
Galvanic Corrosion	Corrosive condition that results from contact of different metals	Uniform damage, scale, surface fogging or tarnishing	Emission of mostly molecular hydrogen gas in a diffused form
Stress Corrosion Cracking	Mechanical tensile stresses combined with chemical susceptibility	Micro-macro-cracks located at shielded or concealed areas	Initially produces scale-type indications. Ultimately leads to cracking

The various processes of corrosion are affected by several factors. Among these are the type of material selected for the application, the heat treatment of the material, the environment of the application, and the presence of any contaminants in the material itself.

ES.1.2.2 Corrosion Detection Technology Areas

Corrosion detection is a subset of the larger fields of NonDestructive Evaluation (NDE) and NonDestructive Inspection (NDI). Many of the technologies of NDE/NDI lend themselves to the detection, characterization and quantification of corrosion damage. The following table summarizes the major advantages and disadvantages of the primary corrosion detection and characterization technologies.

Table ES-2. Summary of Corrosion Detection NDE/NDI Technologies.

Technology	Advantages	Disadvantages
Visual	• Relatively inexpensive • Large area coverage • Portability	• Highly subjective • Measurements not precise • Limited to surface inspection • Labor intensive
Enhanced Visual	• Large area coverage • Very fast • Very sensitive to lap joint corrosion • Multi-layer	• Quantification difficult • Subjective - requires experience • Requires surface preparation
Eddy Current	• Relatively inexpensive • Good resolution	• Low throughput • Interpretation of output

	• Multiple layer capability • Portability	• Operator training • Human factors (tedium)

Technology	Advantages	Disadvantages
Ultrasonic	• Good resolution • Can detect material loss and thickness	• Single-sided • Requires couplant • Cannot assess multiple layers • Low throughput
Radiography	• Best resolution (~1%) • Image interpretation	• Expensive • Radiation safety • Bulky equipment
Thermography	• Large area scan • Relatively high throughput • “Macro view” of structures	• Complex equipment • Layered structures are a problem • Precision of measurements
Robotics and Automation	• Potential productivity improvements	• Quality assurance • Reliability

The study team encountered a great variety of technologies in various stages of maturity. These technologies are being pursued in university research labs, industry R&D programs and government laboratories. Table ES-3 below summarizes the observed trends in the directions that the various technologies seem to be headed, based on the research and site visits performed in the generation of this sector study.

Table ES-3. Corrosion Detection Technology R&D Trends.

Technology	Observed Trend
Enhanced Visual	• Quantification of corrosion • Automation of image interpretation • Film highlighters for temporary surface modification • Scanner-based systems
Eddy Current	• More sophisticated signal and data processing (pulsed eddy current, C-scan imaging) • More sophisticated sensors (multi-frequency)
Ultrasonic	• More efficient scanning methods (dripless bubbler, gantrys, etc.)

	• Dry couplants (including laser stimulation) • Air coupled ultrasonics
Radiography	• Single-sided methods (backscatter) • Three-dimensional image processing (computed tomography)
Technology	**Observed Trend**
Thermography	• Time domain analysis (thermal wave imaging) • Multi-spectral (dual-band infrared) • Three-dimensional image processing (computed tomography)
Robotics and Automation	• Attached computer-controlled positioning mechanisms • Gantrys (multi-axis) • Crawlers (including vertical and inverted surfaces)
Data fusion	• Image processing (color coding, three dimensional, etc.) • Image correlation (C-scan, etc.) • Multi-mode NDI
Sensor fusion	• Currently only attempted within a single technology (e.g., eddy current, infrared) • No observation of research into combining two different sensors into a single probe for simultaneous measurements

We note that it is also very important to know that corrosion does not exist. If deep corrosion could be detected reliably and efficiently, the substantial costs associated with teardown inspections would be dramatically reduced. Maintenance plans typically call for teardown of certain structure to determine their condition. If an NDI method could accurately determine the level of corrosion, including the probability that there is no corrosion present, then the huge costs asssociated with teardowns could be avoided. This would support the concept of condition based maintenance by providing an accurate assessment of the condition of the system in question.

ES.1.3 Technology Applications

The areas where corrosion occurs, the materials in which it occurs, and the conditions under which it occurs all combine to make the inspection for and detection of corrosion a very difficult matter. All defense systems experience some sort of corrosion and there are certain known problem areas for land, air and sea applications. The typical process of finding and identifying corrosion begins with visual inspection. Clearly, any damage that can be observed by visual means will require closer inspection. Field inspection by other means usually entails eddy current and/or ultrasonic inspection. These types of inspections can generally be accomplished during routine maintenance without impacting operational availability. If additional inspection is determined to be necessary, it is normally done by specialists under controlled conditions, such as in a protected space or in an NDI laboratory.

ES.1.3.1 Corrosion Costs

Combined, the defense establishments of the three NATIBO sponsor countries - the U.S., Canada, and Australia - expend on the order of $2.1 Billion per year on corrosion related activities and equipment. These costs could be reduced with better NDE/NDI and corrosion detection technology, and productivity improvements in the maintenance areas. The magnitude of these expenditures would make the area of corrosion detection, characterization, and prevention a tempting target for future R&D.

One interesting point that was uncovered during the costs analyses is that the cost per aircraft for most types, and especially for large aircraft, has increased dramatically in the past seven years. The general trend, as would be expected, is that as aircraft age, the relative cost of maintenance and repair attributable to corrosion increases significantly.

ES.1.3.2 Corrosion Detection Technologies R&D and Application Activities

There are a number of different research and development activities ongoing in the field of corrosion detection technologies. A major thrust of the research being conducted is for detecting hidden corrosion in aircraft. The military is considered the primary corrosion detection technology driver. This is due in part to the fact that military systems typically are fielded longer, have higher cycle rates and operate in more corrosive environments than commercial systems. And with the continual decline in defense spending, the service life for defense systems will be extended even longer with a consequent focus on reducing maintenance costs for these existing systems.

As systems age, corrosion becomes one of the largest cost drivers in life cycle costs of weapon systems. Technology has been identified as one of the primary means of reducing the impact of corrosion on weapon systems. Throughout the military, corrosion is regarded as less a safety or technical issue but rather more of an economic issue. This is because the corrosion problems encountered by the military in their defense systems has been detected and repaired before it could become a safety problem. Currently, corrosion prevention is a higher priority within the military sector. The DoD S&T community is researching a number of different technologies to achieve corrosion reduction in defense systems.

Within the United States, the USAF is considered to have the largest corrosion detection technology development program among the three Services. The Navy has the largest monetary investment in corrosion research. The Navy is also considered to have the best corrosion maintenance and training practices. The DoD, NASA, and FAA have all established Aging Aircraft Programs to address such key problems as corrosion prevention and detection.

The Canadian Department of National Defence (DND) has several different departments and laboratories researching corrosion detection and corrosion prevention technologies. These groups are extremely effective in coordinating their research activities. A predominant focus of their research is on corrosion prevention and detection in aircraft. The AVRD/E Structures and Materials Group oversees R&D efforts in corrosion prevention and detection.

The major Australian DoD research arm involved in studying corrosion detection technologies is the Defence Science and Technology Office. The Office has a number of divisions addressing different corrosion issues and technologies to employ to detect and correct corrosion. There is a high level of coordination between these divisions. The main focus of their work is on aging aircraft as well.

ES.1.3.3 Corrosion Detection Technology Industry Demographics

Corrosion detection is one small niche market of the NDE/NDT industry. NDE/NDT equipment suppliers and service providers are not dependent upon the corrosion detection market for their livelihood. In fact, the NDE/NDT end user industries run the gamut, including defense aerospace, commercial aerospace, automotive, shipbuilding, chemical/petrochemical, construction infrastructure, electronics/electrical, energy (utilities), ordnance, and railroad.

The industry outlook for each of these technologies varies as does the industrial base supporting development of them. However, the NDE/NDT equipment suppliers are very amenable to custom adapting their equipment for specific applications for a fee.

The industrial base for visual, ultrasonic, and eddy current equipment is relatively stable.

The base for film-based radiography equipment has been dealt some setbacks in recent years as film use is on the decline with the emergence of real-time radiography, military cutbacks, and user concern with environmental impacts of film processing. The number of major radiographic film suppliers has decreased from four to three, with competition fierce among those remaining fighting for market share in an ever shrinking market.

Non-film based radiography suppliers market is in a state of flux. The market for radioscopy systems has declined due to military cutbacks. However, in response to this, suppliers have branched out to other commercial markets such as the automotive and the electronics industries to shore up their marketplace stance. And, with the development of portable radioscopic systems, new uses for this technology have opened up, such as in-field inspections of pipelines and aircraft.

The number of thermographic equipment and service providers is expanding from a handful to a larger number as the technology matures.

ES.1.4 CONCLUSIONS

ES.1.4.1 Facilitators

ES.1.4.1.1 Heightened Awareness

Due to the 1988 Aloha Airlines incident and the Military Forces' need to extend the service life of military systems three to four times their original design life, there is heightened awareness to the issue of corrosion and how it is a key contributor to system failures and a driving factor in terms of safety, downtime and costs. This need has been underscored by shrinking defense budgets, reduced procurements of new equipment, and increased reliance on modifications and upgrades to current systems.

ES.1.4.1.2 Established Working Groups

There are a number of established associations and working groups addressing the issue of corrosion, both within North America and internationally. The U.S., Canadian and Australian Governments also coordinate on their research in the field of corrosion detection technologies via the Corrosion Sub-Panel of the Technology Panel for Advanced Materials (part of Project Reliance).

ES.1.4.1.3 New Emphasis on Cost Effectiveness/Condition Based Maintenance

As a cost savings strategy and to eliminate the need for unnecessary maintenance, the Services are moving away from routine maintenance where components are replaced based upon length of time in service rather then real need. They are instituting programs where components are replaced based on their condition rather than to conform to a given time-in-service. This move to condition based maintenance will provide incentives to employ newer, more efficient corrosion detection techniques so that personnel will be better able to pinpoint the extent of their corrosion problems and its effect on the structural integrity of the system.

ES.1.4.2 Barriers

ES.1.4.2.1 General Barriers

ES.1.4.2.1.1 Data Not Readily Available

While collecting data for this study, we discovered that recently published NDE/NDT and corrosion detection reports are not showing up in DTIC, Dialog and other literature searches. Most of the publications that are in these databases are dated. Also, in trying to gain data from the depot/field level in regard to maintenance and failure analysis and the role of corrosion in the need to repair and replace parts, it became apparent that this type of information is not easily obtainable and, hence, is not given the visibility it needs at different levels to ensure that these recurring corrosion problems are effectively communicated and that procedures are put in place to rectify the situation. This was true also in the case of trying to quantify the cost of corrosion to defense systems. There is no uniform equation or standard economic model developed of the elements for determining the corrosion costs (though Warner Robins has released a 1998 report that breaks these elements down for aircraft). In a recent development, Tinker Air Force Base has initiated (late 1997) a project to establish an Aging Aircraft database.

ES.1.4.2.1.2 Research is Dispersed

There are a number of different research organizations conducting studies in the area of corrosion detection technologies. However, these groups are widely dispersed within DoD, DND, and the Australian DoD, reducing the visibility of the work being performed. Until recently, there was not a great deal of coordination in the U.S. between these different groups, especially outside of their respective Services, though more coordination has been initiated between these groups as of late. The Canadian and Australian organizations are more effective in communicating their research results within their countries; however, all three countries could benefit by increased coordination and sharing of findings between their research communities. And, there appears to be a disconnect between the operators and the R&D community. The R&D community is focusing on 6.1 and 6.2 research whereas the operators are conducting program specific research, and there does not seem to be effective communication occurring between the different groups.

ES.1.4.2.2 TECHNOLOGY BARRIERS

ES.1.4.2.2.1 Need for Newer Techniques Not Widely Recognized

The general impression that was formed through the numerous site visits conducted by the research team was that most users are satisfied with current techniques. Commercial users are wont to invest in additional corrosion detection technology that cannot be clearly justified in economic terms. Overall, they are satisfied that current technologies and techniques have served to prevent catastrophic losses. They are not informed as to the potential for reduced maintenance and repair costs that could be realized through improved corrosion detection technologies and techniques. There is agreement that the direct and indirect costs of corrosion are substantial; there is not agreement that these costs can be substantially reduced through further investment in corrosion detection and quantification technologies and tools. This dichotomy is best described as a “cost-benefit” question typical of the application of new technologies to existing problems. Particularly in the commercial arena, there is a sense that improved corrosion detection technologies would lead to additional and, in many cases, unneeded maintenance actions.

ES.1.4.2.2.2 NDE/NDT Technologies Developed for Applications Other Than Corrosion

The first concern of structural and materials engineering has been the detection and characterization of defects that can be adequately modeled and therefore predicted; i.e., cracks. NDE/NDT technologies have evolved to support the science of fracture mechanics, a discipline that is now highly developed and quite reliable in predicting the life of complex structures in known cyclic loading environments. These technologies, notably eddy current and ultrasonic, have proven useful for detecting and characterizing the material loss caused by corrosion. However, this is after the fact. The difficulty, and near impossibility, of predicting corrosion has pointed the work in detection technologies more toward detection of cracks than detection of material loss due to corrosion. The fact that corrosion is caused by many interacting processes contributes to this situation.

ES.1.4.2.2.3 Efficiency/Reliability of Newer Techniques and Cost/Benefits Not Well Established

The transition of a new technology from laboratory to field application is difficult. The government has been able to invest in some of the more sophisticated technologies (such as neutron radiography) that would be beyond the reach of commercial enterprises, airlines for example. Typically, a new technology that has been developed in a laboratory is commercialized by a small company, often a start-up. Basically, the marketplace determines the success or failure of a particular technology through customer determination of the cost-effectiveness of each new offering. Without some history that would support improved cost-effectiveness, a new technology or technique faces a large hurdle to implementation on a wide basis.

ES.1.4.2.2.4 Safety Concerns About Radiography Techniques

Although radiography is perhaps the most precise of the corrosion detection, and especially corrosion quantification, technologies, it presents the most serious hazard to the users. Indeed, in many jurisdictions radiographic facilities and operators are required to be licensed. Field operation of x-ray equipment requires that personnel be kept at some distance from the radiation sources. The emphasis on worker safety and concerns for liability judgments serve to impede the wider implementation of radiographic techniques.

ES.1.4.2.2.5 Thermography Perceived as Not Effective or Reliable

Thermography depends on operator interpretation of how an image of the structure in question differs from an image of a perfect or, at least, acceptable, structure. Thus, for every image produced, there must be a means to compare that image against that of a similar undamaged structure. Combined with the fact that thermographic images are somewhat "fuzzy" compared to other imaging techniques (visual, radiographic, etc.), many users remain skeptical of the precision and reliability of thermography as a corrosion detection technology. This is due to the fact that thermographic images are captured by IR cameras that are made up of an array of detectors, each detector contributing one pixel to the overall picture. Thus, IR cameras have much lower resolution than visual photographic processes (in much the same way that a photograph has much better resolution than a television image).

ES.1.4.2.2.6 Human Factors Limitations

Much of the work in inspecting for corrosion is repetitive and, in a word, tedious. Take into account that much of the work is done in awkward locations and sometimes under adverse environmental conditions (darkness, cold, etc.) Added together, the problem of inspection for corrosion goes well beyond that of just the technology of the sensing device and the processing of the information. It must include an array of human factors that will limit the overall effectiveness of the inspection process.

ES.1.4.2.3 Policy/Fiscal Barriers

ES.1.4.2.3.1 Cost of Corrosion Difficult to Calculate

Determining the costs of corrosion in the life cycle of a system is difficult to calculate. There currently is no baseline for this type of measurement and no good cost data at present. Hence, the costs of corrosion are not considered upfront in the acquisition cycle since no benchmark for measuring the impact of corrosion has been established. In addition, an effective cost/benefit analysis of the cost savings generated by implementing a corrosion detection technology is difficult to quantify.

ES.1.4.2.3.2 Commercial Airlines/Military Have No Economic Incentive to Improve Probability of Detecting More Corrosion

In commercial operations, there are cases where original equipment manufacturers have specified that when corrosion is determined to be less than 10% loss per layer, the operator has the choice of repairing the damaged area immediately or deferring the repair until the loss reaches 10%. However, the second option requires that the corroded area be re-inspected periodically. This is a heavy disincentive to the deployment of systems capable of detecting corrosion below 10% if a system capable of detection of 10% is defined to be adequate. Correcting corrosion damage at short intervals is inefficient, even though the immediate maintenance action may prevent larger repairs later. Operators typically want to perform all corrosion repairs during a single downtime to minimize overall downtime. This leads operators to defer corrective actions until the greater 10% material loss is detected.

Perhaps the most attractive economic incentive to the commercial airlines would be improving the productivity of the inspection process, thereby reducing the cost of maintenance, assuming that that can be done without compromising the safety or the service life of the aircraft. Economic incentives would surface if more developments were to occur in the area of condition based models where they could use the knowledge and exert control over how a corroded component is repaired and treated and tracked (such as what is presently used for fatigue and crack growth analysis), rather than simply removing all corrosion in all cases, which can end up damaging the structure even more. In other words, corrosion models are needed to determine the consequence of repairing it or treating it, or leaving it alone to make better informed decisions. (The models would take the effects of the corrosion damage on the fatigue life of the aircraft, and require accurate quantitative NDT input).

With regards to the military, employing new technologies cost money and, as with the airlines, this cost must be weighed against the return on investment to the facility. Without quantitative cost data to support a decision to invest in new technologies, most of the actual users would not incur such an expense at the depot level.

ES.1.4.2.3.3 Cumbersome, Lengthy Process for Emerging Techniques to Gain Wide Acceptance/FAA-OEM Approval

Currently, Service Bulletins are developed by the Original Equipment Manufacturers (OEMs) to deal with specific maintenance problems. The FAA may issue Airworthiness Directives (ADs) to deal with problems of a more urgent nature. Service Bulletins receive FAA approval before issuance. Airline maintenance operations may implement the Service Bulletin through an Alternate Means of Compliance (AMC). While the AMC is valid for the developing airline, it is not useable by another maintenance organization. In their quest to control costs, airlines seek lower cost alternatives to mandated inspection and repair requirements. The approval process for an AMC is lengthy and expensive. Thus, any new technology that has promise to improve the inspection process and the productivity of the maintenance operation faces a not inconsequential approval cycle before it is generally accepted in the customer community.

ES.1.4.2.3.4 Increased Training Requirements for Technicians to Use Different Technologies

Every different corrosion detection technology will entail different training requirements. Eddy current and ultrasonic sensors produce displays that require a high degree of sophistication to properly interpret. Improved processing of newer techniques, such as stepped pulsed eddy current, provide c-scan images that are much more intuitive but still require expert interpretation, especially in determining when a particular threshold has been exceeded and some expensive repair process is required. The range of technologies also expands the knowledge required to interpret the results. Thus, for a technician to be considered fully qualified in all areas necessary to perform a complete corrosion inspection, many more skills are required than before. Coupled with this is the fact that the number of trained NDT inspectors is dwindling due to base closures and consolidations and turnover at the maintenance level. Hence, the Services are experiencing a loss of corporate memory through retirement of key personnel.

ES.1.5 RECOMMENDATIONS

ES.1.5.1 Request the Corrosion Sub-Panel of TPAM Perform Added Coordination Activities

To ensure the widespread dissemination of published reports on corrosion and that information regarding corrosion detection techniques, advances, and implementation are effectively coordinated throughout the NDE/NDI community, the Corrosion Sub-Panel of TPAM should be approached about taking on the responsibility of:

- Coordinating and promoting interaction between the Services and identifying common problems
- Establishing a central repository of reports and other corrosion related information
- Improving report distribution
- Pooling information on system failures/corrosion problem areas
- Establishing a Point of Contact database of technology experts (placed online and updated annually) so that timely consultation on specific corrosion related issues can be achieved.

If buy-in to these coordination activities is achieved, perhaps this panel could enlist the aid of the NTIAC to support these efforts.

ES.1.5.2 Appoint Recognized Champions to Push for Corrosion Agenda and New/Higher Fidelity Techniques

To ensure that the entirety of system life cycle costs are considered in the procurement process, identify and enlist military champions to “market” the savings to Programs/Program Managers from 1) building into the design of the system protective measures to protect against corrosion and 2) including processes for detecting corrosion problems early in a system’s life cycle. Additionally, the logistics community should be made aware of the importance of corrosion prevention and corrosion control in planning for the life cycle support of systems and in developing R&D requirements for extending the life cycle of weapon systems. These champions could emphasize the importance of considering corrosion costs as an independent variable for determining life cycle costs and push for establishing benchmarks for measuring the impact of corrosion on the service life of a system. In order to better define these costs, the champions could recommend that economic models be developed that address the costs of corrosion in the life cycle of the system and address the savings realized by planning for corrosion detection upfront and detecting corrosion early on in the system’s maintenance life. In addition, these champions could strive to establish an integrated approach to tackling corrosion issues, ensuring that Integrated Product Teams consisting of structural engineers, NDE/NDI personnel and researchers address these issues in a joint fashion.

ES.1.5.3 Target Insertion/Demonstration Program

In order to demonstrate the benefits derived from employing a certain corrosion detection technology(s), a widely applicable, high payoff, dual use insertion/demonstration program would be an ideal mechanism. A candidate for an insertion/demonstration program might be multi-sensor and multiple data fusion, incorporating automation/robotics as deemed feasible. These suggestions support the findings of the National Research Council, and have met with widespread backing from the members of the NDE/NDI community. Industry and government input would need to be solicited to develop a DoD/DND/Australian-specific program that involves the fusing of as many NDE techniques as possible. Researchers, developers and end-users would participate in the identification and selection process.

ES.1.5.4 Streamline Process for Inserting Newer Techniques into OEM Maintenance Procedures

The feedback from the research community through the OEMs back to the users and operators of the systems should be shortened. It should be possible to incentivize this process to reward improvements that can enhance system reliability and extend the life of a system while reducing the cost of inspection and repair. The use of electronic updates to inspection and repair manuals can reduce the administrative delay.

ES.1.5.5 Increase Collaboration Between the Military Departments and University NDE/NDT Departments on Training

Training is usually an afterthought following the development of new inspection technologies and tools. It should be possible to procure integrated training along with any new inspection tools. Such training would be essential until each using organization was able to develop a core of expertise and thereby be able to conduct their own training programs.